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Abstract

Two Voyager spacecraft are currently exploring the outer reaches of the heliosphere in search of the termination shock, and the heliopause boundary with the interstellar medium. With the potential of continuing spacecraft operations until about 2020, there is a high likelihood of one of the spacecraft penetrating one or both of these heliospheric features.

This paper provides a description of the Voyager Interstellar Mission - the mission objectives, the spacecraft and science payload, the Mission Operations System, and key elements of the mission operations concept including a description of multimission and automation implementations that enable reduced flight team staffing. Also included is a brief history of the Voyager Project and recommendations for consideration by future projects of specific spacecraft/ground trades and implementations as potential ways of reducing mission operation costs

Introduction

The Voyager 1 and 2 spacecraft (S/C) have been in flight for over 18 years. During the first twelve years of this time period, the two S/C returned a wealth of scientific information about the planetary systems of Jupiter, Saturn, Uranus, and Neptune, and the interplanetary medium between Earth and Neptune. At the beginning of 1 990, after over twelve years in flight, the two Voyager (VGR) S/C began a new scientific endeavor, the Voyager Interstellar Mission (VIM). This missions purpose is to characterize the interplanetary medium beyond Neptune and to search for the transition region between the heliosphere and the interstellar medium. With the potential of continuing S/C operations until the 2020 time period, the possibility exists for reaching and passing beyond the heliopause, providing the opportunity to sample and characterize the interstellar medium. This achievement would provide an admirable finale to one of the greatest scientific adventures of spaceflight, if' not of mankind.

Voyager History

The Voyager Project began in 1972 under the name Mariner Jupiter/Saturn 1977 (MJS77) Project. Prior to launch, the project name was changed to Voyager. The Voyager mission design took advantage of a rare geometric arrangement of the outer planets in the late 1970s and the 1980s (occurs approximately every 175 years) which allowed for a four-planet tour by a single S/C with a minimum of propellant and trip time. By using the gravity of each planet to bend the S/C flight path and increase its heliocentric velocity enough to deliver the S/C to the next destination, the flight time to Neptune was reduced from 30 to 12 years.

While the primary objective of the Voyager Project was limited to conducting exploratory investigations of the Jupiter and Saturnian systems (planet, magnetosphere, satellites, and rings) and the interplanetary medium between Earth and Saturn, the mission design included the option for a continuation of the Voyager 2 mission to Uranus and Neptune. The success of the Voyager 1 Saturn encounter allowed this option to be exercised and successful encounters with all four giant outer planets were achieved. Figure 1 illustrates the trajectories of the two Voyager S/C through the solar system and includes the closest approach dates at each planet.

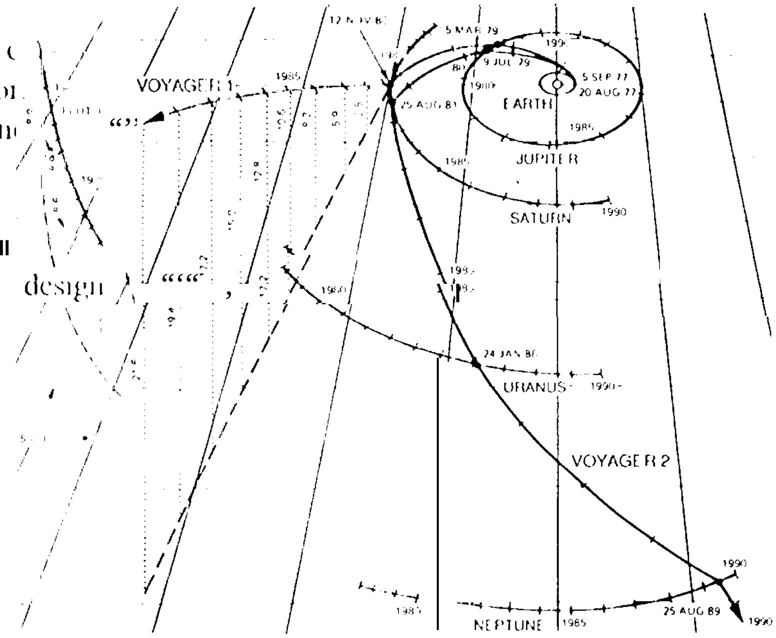

Figure 1 - Voyager 1 & 2 Interplanetary Trajectories

The 825 Kg Voyager S/C [1,2] in its in flight configuration is illustrated in Figure 2.

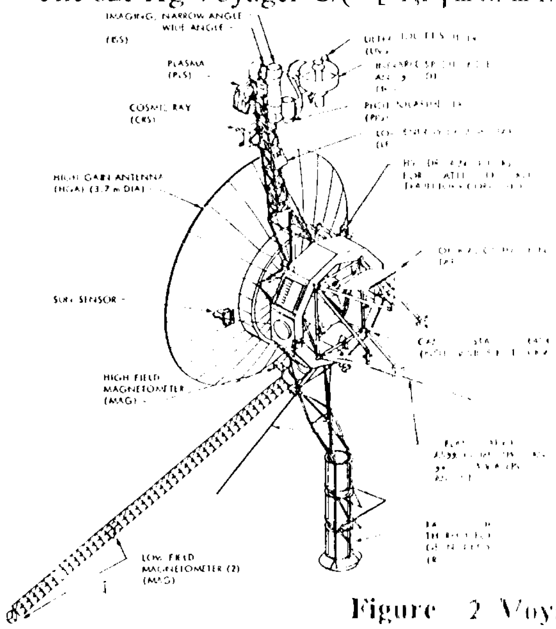

Figure 2 Voyager S/C

Key S/C Characteristics

- Three-axis stabilization: sun sensor, star tracker, 3-axis gyros
- Two degree-of-freedom scan platform
- S-band uplink/downlink, X-band downlink
- Polygon electronics bus structure: 10 bays
- Radioisotope Thermoelectric Generator (RTG) power supply
- Reprogrammable computers: Computer Command Subsystem (CCS), Flight Data Subsystem (FDS), Attitude and Articulation Control Subsystem (AACS)
- Hydrazine propulsion for attitude control and trajectory correction
- Thermal blankets and louvered bays/assemblies
- Digital Tape Recorder (DTR); 8 tracks, 536 megabits capacity
- Six Fields and particles instruments, five optical instruments, radio science

From launch, in 1977, through the Neptune encounter in I 989, periodic S/C and ground system configuration changes were necessary to deal with: a better understanding of the actual S/C performance capabilities; S/C performance changes due to increased age or subsystem anomalies, and; S/C engineering changes resulting from the ever increasing operating distance from the Earth and Sun [3,4,5]. The most serious S/C performance change occurred onboard Voyager 2 in April, 1978, when its primary receiver and the tracking loop circuit on its backup receiver failed. This double failure meant that the uplink carrier reception capability of the S/C had a bandwidth of only ±100 Hz instead of the normal ± 100 Khz. This eliminated the receivers capability for tracking the always present Doppler induced frequency variations. As a result of these failures, ground system modifications had to be implemented to provide the capability to vary the, uplink carrier frequency transmitted by a Deep Space Network (DSN) tracking station in a manner that presented a near constant carrier frequency to the S/C receiver. The techniques developed in 1978 to cope with this anomaly are still in use today. Key engineering changes resulting, from a better understanding of the actual S/C performance and the ever increasing operating distance from the Earth and Sun are summarized in Table 1,

Change	Benefit
• 1979 - VGR 1&2 - Implemented image motion compensation using gyro drift turns	• Allowed radio science limb tracking and target body tracking for close satellite flybys
• 1979 - VGR 1&2 - Implemented automated onboard DTR momentum cancellation capability	• Reduced interaction between the DTR and resultant S/C motion
• 1985 - VGR 2 - Qualified thrusters to operate at 4 msec pulses rather than the normal 10 msec	• Reduced attitude control drift rate resulting in reduced image smear during long exposures
• 1985 - VGR 2 - Implemented on-board imaging data compression and Reed Solomon data encoding	• Allowed near Saturn-level volume of imaging data to be returned at Uranus and Neptune distances
• 1985 - VGR 2 - Implemented increased gyro drift turn rate capability	• Allowed image motion compensation for close Miranda flyby observations
• 1985 - VGR 2 - Modified Parkes antenna for telemetry data reception - arrayed with Canberra DSN antennas	• Increased telemetry reception data rates at Uranus distance
• 1989 - VGR 2 - DSN 64 M antennas enlarged to 70 M	• Increased telemetry reception data rates at Neptune distance
• 1989 - VGR 2 - Modified Very Large Array (VLA) antennas for telemetry reception arrayed with Goldstone DSN antennas	• Increased telemetry reception data rates at Neptune distance
• 1989 - VGR 2 - Lengthened camera exposure capability	• Needed to accommodate long exposure duration's at Neptune
• 1989 - VGR 2 - Implemented two new image motion compensation techniques	• Needed to minimize image smear during long exposure duration's at Neptune

Table 1 - Summary of Key Engineering Changes

While the two Voyager S/C have suffered partial engineering subsystem failures and performance degradation, both S/C are still fully capable of supporting the VIM mission/science objectives. Built-in redundancy and the ability to reprogram the three flight computers have permitted adequate work-arounds for the problems experienced to date. However, because of subsystem failures, each S/C is now vulnerable to a single point of failure. On Voyager 1, one of the FDS memories failed in 1981, and failure of the second FDS memory would result in end-of-mission. On Voyager 2 the primary receiver failed in 1978, however, failure of the second receiver would result in loss of command reception capability, but not end-of-mission. A back up sequence stored in the Voyager 2 CCS memory would continue to operate the S/C and return science data until 2017.

The limiting lifetime consumable on both S/C is electrical power. The RTGs currently provide 336 watts (Voyager 1) and 338 watts (Voyager 2) of power and are degrading at a rate of about 5.2 watts/year. Extrapolation of the performance-to-date indicates an ability to support science data return until approximately 2020. Hydrazine fuel is not a factor with the quantity available (34 kg on Voyager 1 and 36 kg on Voyager 2) being sufficient to maintain attitude control well beyond 2020.

Voyager Interstellar Mission

The fundamental VIM science objective is to investigate the heliospheric and interstellar medium and to characterize the interaction between the two. The accomplishment of this objective requires the continued operation of the two Voyager S/C far beyond their initial lifetime requirement of the four years necessary to investigate the Jupiter, and Saturn systems. After over eighteen years of flight, both the engineering subsystems and the seven science instruments capable of providing data related to the VIM objectives (MAG, PLS, LECP, CRS, PWS, PRA, UVS, see Figure 2 for legend) are still functioning, with some performance degradation, on each S/C. Typical VIM science objectives are summarized in Table 2.

- Characterize the evolution of the solar wind with increasing distance from the Sun
- Observe solar cycle variation in the distant interplanetary medium
- Investigate latitudinal variations in the interplanetary medium
- Search for low-energy cosmic rays
- Characterize particle acceleration and plasma thermalization mechanisms in the interplanetary medium
- Search for evidence of interstellar hydrogen and helium from the interstellar wind
- Observe and characterize the termination shock of the supersonic solar wind
- Observe and characterize the heliopause
- Observe the local interstellar medium and associated radio emissions
- Observe radio emissions from the Sun and solar wind
- Monitor the extreme ultraviolet emissions of the Sun

Table 2 - Typical VIM Science Objectives

The two Voyager S/C are pursuing these VIM science objectives from positions above and below the ecliptic plane. The Voyager 1 Saturn flyby resulted in the S/C being deflected out of the ecliptic plane to the north at an angle of 35.5° in the general direction of the solar apex. Voyager 2 was deflected by Neptune in a direction south of the ecliptic plane at an angle of 48° and about 90° away from the direction of Voyager 1. Figures 3 and 4 illustrate S/C heliocentric distance and heliocentric latitude (with respect to the ecliptic plane) information.

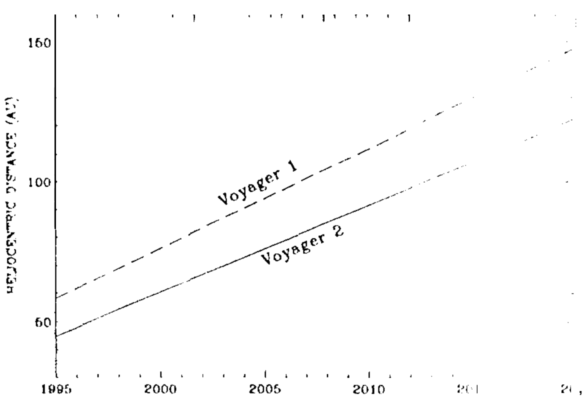

Figure 3 - Heliocentric Distance

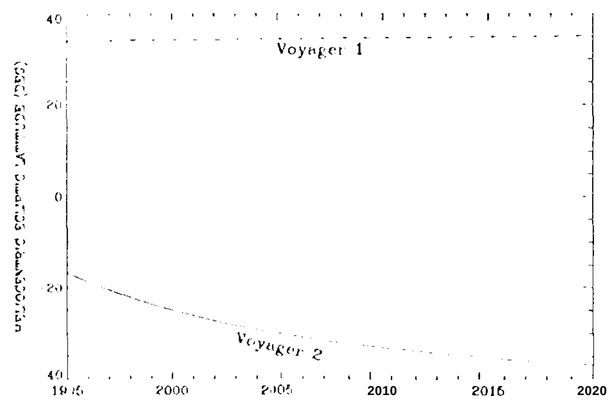

Figure 4 - Heliocentric Ecliptic Latitude

Recent estimates of the termination shock location range from 60 to 105 astronomical units (AU), and the heliopause location estimates range from 116 to 177 AU [6]. Both of these goals may be achievable within the projected lifetime of the two Voyager S/C. Voyager 1 is currently about 64 AU from the Sun, traveling at a speed of about 3.6 AU per year, and will reach 150 AU in 2020. Voyager 2 is currently about 49 AU from the Sun, traveling at a slower sped of about 3.1 AU per year, and will reach 125 AU in 2020.

Science data return during VIM relies primarily on real time telemetry data capture using 34M DSN tracking stations. The nominal data rate is 160 bps of which 150 bps is science data and 10 bps is engineering data. Sixteen hours per day of tracking support per S/C is the target for science data acquisition. This target has been achievable in the past but the expected future increase in missions being supported by the 34M DSN tracking stations will result in reduced tracking station availability for VIM. As tracking support is reduced, the ability to characterize the heliospheric medium is degraded. Minimum science data acquisition requirements vary between 12 and 4 hours per day per S/C depending on the specific investigation. In addition to the real time data, 48 seconds of high rate (115.2 K bps) PWS data is recorded weekly onto the DTR of each S/C. These data are played back every 6 months providing increased temporal and spectral resolution snapshots of the plasma wave information. High rate PWS recording and playback will continue until 2010 (Voyager 1) and 2012 (Voyager 2) when telecommunications capability will no longer support the minimum DTR playback data rate of 1.4 Kbps.

Mission Operations System Description

The Mission Operations System (MOS) is the collection of hardware and software, facilities, personnel, and procedures utilized to remotely monitor and control the Voyager S/C, and deliver data products to engineering and science users. Included in the MOS are the Ground Data System (GDS), making extensive use of institutionally supported multi-mission ground data system elements, two process oriented (uplink and downlink) flight operations teams, and a mature collection of operating procedures that have evolved throughout the mission.

Ground Data System

The systems that comprise the Voyager GDS (circa 1996) are the Telemetry System, Command System, Sequence System, S/C Analysis System, Data Records System, and Simulation System. These systems are distributed across the globe, from the DSN tracking stations to the facilities at the Jet Propulsion Laboratory (JPL). Voyager's GDS has been extensively modernized since the Neptune encounter in 1989. With the exception of a few elements utilized for sequence generation, S/C analysis and support of remote investigators, the entire GDS is composed of tailored multimission components. The GDS core processing elements are of the same lineage as those supporting Cassini, the Mars program, and other new missions, and are kept current through an active test program providing periodic GDS upgrades.

Connectivity between the DSN stations and the local GDS at JPL is accomplished via the Ground Communication Facility (GCF). Network communications links providing mission support include a "critical" Local Area Network (LAN) which connects all Voyager-resident elements (approximately twenty-five UNIX workstations) of the GDS. This LAN is connected across a gateway to the GCF and to the DSN tracking stations, and is the carrier of incoming telemetry and science data, and of outgoing command traffic. Connected to this IAN are all the multimission components of the GDS, as well as other gateways leading to other projects and their mission-dependent LANs. Figure 5 provides an overview diagram of the Voyager GDS.

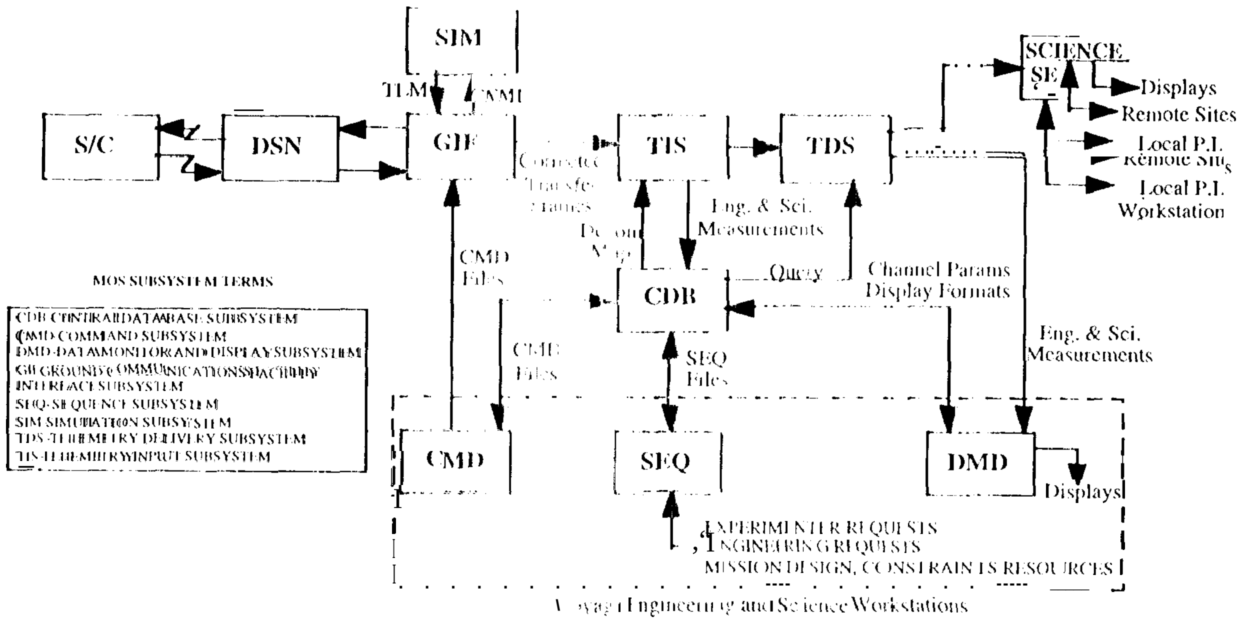

Figure 5 - Voyager GDS

Multi-mission telemetry front-end processing elements (GIF, TIS): (1) detect and remove frame and packet format structures; (2) remove data transport artifacts and data redundancy, and; (3) provide recovery from lost, noisy and disorganized data. Data are broadcast over the LAN to project work stations in real-time and also stored in the CDB for later access. Workstation access to retrieve non-real-time data uses the data retrieval tools DMD and TDS.

In the S/C telemetry analysis area an automated telemetry alarm monitoring tool was developed during the VIM to enable the elimination of around-the-clock mission control support. This tool, VAMPIRE (Voyager Alarm Monitor Processor Including Remote Examination), processes the broadcast telemetry data, detects alarm conditions, and initiates contact with on-call personnel via a secure dial-back modem when certain anomalous conditions occur. A second automated tool MARVEL (Monitor/Analyzer Of Real-time Voyager Engineering Link), developed pre-VIM, monitors CCS/FDS telemetry data and displays on a work station screen any conditions that are not as predicted. These automation tools have proved to be valuable in maintaining high mission reliability during significant downsizing of the flight team staffing level.

Since the Neptune encounter, the Voyager Data Records System (DRS) has evolved from a project-unique mainframe processing system to a workstation-based server capability. The DRS "science" server is connected to flight-critical portions of the GDS through a gateway to satisfy security requirements. Connection in this manner allows the science community timely and uncomplicated access to science processing functions, stored data, standard displays, etc. The server processes raw packetized science and instrument health monitoring data, and provides short term data storage. The server supports the generation of Experiment Data Records (EDRs) which are electronically transferred to the science team institutions.

The Sequence System relies on a mixture of Voyager-unique and multimission sequence generation software. All components of the Sequence System have transitioned, or are in the process of transition to UNIX platforms. The Voyager-unique portions Of the system provide for sequence block parameter definition & editing, sequence constuction and sequence validation. Multimission components interface to the Command System (a fully multimission system) where command generation, translation, transfer to a DSN station and radiation to the S/C occur.

It was mentioned earlier that Voyager actively pursues a testing program to maintain currency with the latest multimission capabilities. This is accomplished with the use of a test bed where new software is installed and basic capabilities tested in a flight-like environment. The Voyager test bed is typically composed of several flight workstations and a file server. The Voyager test bed configuration is transitory, and at completion of any test activity, workstations are reconfigured for flight support using the current operational version of GDS software.

Flight Team Organization

The Voyager flight team organization is built around the two basic operation processes (uplink and downlink). Figure 6 illustrates the Voyager Flight Team Organization with an Uplink Team and a Downlink Team, and the functions performed. Additional operations functions include project and mission management, administrative support, and support of multimission and Voyager-unique hardware and software updates, including development, testing, and configuration management. The current flight team staffing level is about 25 people with team personnel cross trained to perform multiple operations functions. This cross training, combined with the deletion of selected lower priority operations tasks, is essential to accomplishing the necessary functions with the limited personnel available for mission operations support. With further staffing reductions, additional cross training and task deletions will be necessary.

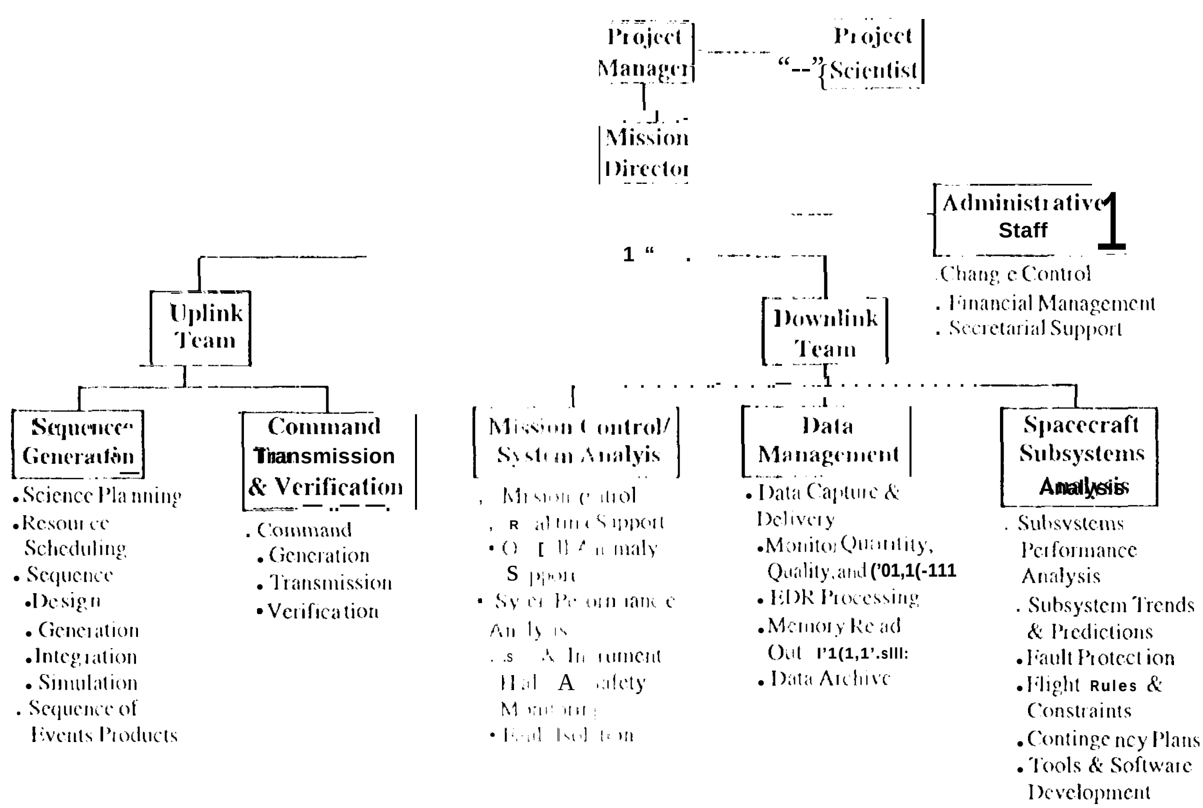

Figure 6 Flight Team Organization

Uplink Team Description

The Uplink Team performs all functions necessary to generate S/C event sequences, command files, and to transmit and confirm commands sent to the S/C. Two basic processes, the sequence generation process and the real-time command process, provide the mechanism for accomplishing these functions.

The sequence generation process begins with the collection of S/C activity requests (science and engineering), which are combined into a conflict free sequence design (a timeline of sequence events). Based on this sequence design, a time ordered listing of all S/C events is generated and a sequence simulation and validation performed. A command file is then generated, validated for correctness, and made available for transmission to the S/C.

The real-time commanding process is used to load S/C event sequences and modify the on-board S/C configuration and/or the executing sequence. These operations consist of generating the real-time command request, coordinating and reviewing the request, negotiating the DSN coverage for uplink transmission and downlink verification, generating the command file, transferring it to the DSN, and monitoring the transmission of the commands and the verification of the S/C receipt of the command a Round-Trip Light-time (RTLT) later. The long RTLTs involved (17 hours for Voyager 1 and 14 hours for Voyager 2) result in command verification probably occurring with a different DSN station and different project personnel than performed the command transmission.

Downlink Team Description

The Downlink Process begins at the S/C where state, status, and instrument observation samples are integrated into a formatted data stream for transmission to DSN tracking stations. The Downlink Process ends with delivery of committed data products to science investigators.

The Downlink Team is responsible for the capture, conditioning, and delivery of science and ancillary data committed by the project to experimenters, as well as, all data required for monitoring the status of the Voyager S/C.

The Downlink Team also provides analysis of S/C and science instrument performance and health. This team evaluates S/C and instrument status against expected performance and initiates recovery actions for all S/C anomalies. The Downlink Team provides inputs for the uplink process as necessary to generate engineering calibration and performance data needed to evaluate S/C performance and health, and provides any necessary S/C state and status data to predict S/C behavior for real time monitoring.

Mission Operations Concept

Voyager mission operations consists of maintaining S/C health and safety while obtaining sufficient Fields, Particles, and Waves (FPW) science data to satisfy the VIM objectives. The key elements of the operations concept for accomplishing these two principle objectives includes: (1) a S/C sequencing strategy that minimizes the sequencing effort required, while maintaining a sufficient level of mission adaptivity; (2) minimize real-time mission control support by reliance on an automated telemetry alarm monitoring tool (VAMPIRE) that alerts flight team personnel in the event of out-of-tolerance S/C conditions; (3) automated on-board fault detection and safing for critical S/C capabilities; (4) a long duration onboard science data acquisition sequence to protect against loss of command reception capability and; (5) a power utilization plan consistent with the expected power availability profile.

Sequencing Strategy

The VIM sequencing strategy is based on having a continuously executing sequence of repetitive science observations and engineering calibrations called a "baseline sequence" stored on-board each S/C. Also stored in the sequence memory of each S/C is the S/C pointing information necessary to keep the boresight of the HGA pointed at the Earth until approximately 20?.() allowing continuous communication capability with each S/C. Augmentation of the baseline sequence with non-repetitive science or engineering events use either an "overlay sequence," or a "mini-sequence." The difference between these two types of augmentation sequences is that the overlay sequence operates for a fixed interval of time, currently six months, and contains all of the baseline sequence augmentations for that time interval. The mini-sequence is focused on accomplishing a single augmentation need and not a regularly scheduled activity but is done on an as needed basis. Both types 01 sequences are developed and transmitted from the ground.

In the event command capability is lost, another sequence element, the "Backup Mission Load," (BML) provides the mechanism for continued science data acquisition without further ground interaction. A BML is stored on-board each S/C and contains the necessary instructions to modify the continuously executing baseline sequence to maintain the continued return of basic FPW data.

All of these sequence elements use pre-defined, and validated, blocks of commands to accomplish specific S/C functions. While the ability to use pre-defined blocks of commands greatly reduces the effort required to generate and validate a sequence of commands, there is an inefficiency in the number of memory words needed to accomplish a given function. The VIM science data acquisition requirements, sequencing strategy, and available CCS memory space support the use of pre-defined blocks of commands.

Baseline Sequence

The baseline sequence is a set of instructions stored in the CCS memory and composed of repetitive S/C activities which execute continuously throughout the VIM to return the basic FPW science data. Eleven "S/C block routines" stored in the (X'S ll]c I])0I% are used by the baseline sequence to accomplish the desired S/C activities. During normal operations, each S/C performs the repetitive baseline sequence science and engineering activities described in Table 3.

- continuous collection and return of cruise science data at 160 bps
- Weekly recording of one frame of High Rate PWS data
- playback Of six months of recorded PWS data C\'cl)' () 111011111s
- execution of a magnetometer calibration roll maneuver (MAGROL) every 3 months
- execution of a HGA/sun sensor calibration maneuver (ASCAL) every 6 months
- execution of a PMPCAL once a month (Plasma Wave, Magnetometer Subsystem, Field Particles Waves Periodic Engineering & Science Calibration)
- perform Digital Tape Recorder maintenance twice a year
- perform gyro conditioning and CCS timing test every 3 months

Table 3 - Baseline Sequence Activities

overlay or Mini-Sequence

Overlay sequences are used to augment the continuously executing baseline sequence and are prepared on a regularly scheduled basis, currently 6 months. The overlay sequence provides a mechanism for incorporating non-repetitive science and engineering events into the S/C sequence of activities executing in combination with the baseline sequence. The acquisition of UVS observations, which requires pointing of the scan platform, is the primary driver for the regularly scheduled over lay loads. Around the turn of century, the available electrical power will no longer support the use of the scan platform and the UVS instrument. At that time, the use of' overlay sequences will probably end and mini sequences will be used to augment the baseline sequence as needed. 'i'able 4 lists typical events in overlay sequences:

- UVS stellar and heliospheric observations;
- two additional MAGROLs per year per SK';
- additional high rate PWS records and DTR playbacks;
- DTR playbacks to recover data when the baseline sequence playback was not captured on the ground;
- CCS/FDS/AACS memory readouts
- updates to BML and Fault Protection Algorithms
- modifications to baseline sequence

Table 4 . Overlay Sequence Activities

Mini-sequences also augment the baseline sequence but are prepared on an as needed basis rather than on a regularly scheduled basis. These sequences are usually intended to perform a specific function rather than the multiple functions as performed by an overlay sequence. A mini-sequence may be used to replay DTR playback data not captured on the ground, respond to a S/C anomaly, or record and playback increased high rate PWS data when the termination shock is encountered.

Backup Mission load

The BML provides on-board automated protection against the loss of command capability to both **SK'.** Without command capability, the S/C must continue to operate with the instructions previously stored in the CCS memory. The BML, in conjunction with the baseline sequence, provides this automated protection against loss of command capability. The BML modifies the baseline sequence to provide FPW data for as long as the S/C continues to function. BML modifies the baseline sequence to limit S/C activities and configures the S/C for compatibility with the 10ss of command capability.

Real Time Mission Control

Mission control support has the responsibilities of monitoring S/C health, primarily by monitoring S/C alarm limits, ensuring the DSN support occurs as planned, and the transmission and verification of' commands. During the prime Voyager mission, real time mission control support was provided around the clock. With the reduced flight team staffing during VIM and the acceptability of increased risk during an extended mission, real time mission control is limited to weekday prime shift and special off shift events (commanding, DTR playbacks, attitude maneuvers). The implementation of the VAMPIRE automated alarm monitoring capability has made this arrangement acceptable with only a slight increase in the risk to data acquisition due to reduced DSN coordination during scheduled DSN tracks

Fault Protection and Anomaly Response Capability

Each Voyager S/C has Fault Protection Algorithms (FPAs) stored on-board that are designed to recover the S/C from otherwise mission-catastrophic failures. They are mostly implemented in the Voyager's CCS, while a few are in the AACS. In the CCS, FPAs are invoked by interrupts received from external as well as internal CCS sources, and followed by preprogrammed responses. Table 5 describes the five FPAs that are currently stored in the CCS.

- AACS Power Code Processing monitors AACS status information and issues pre-programmed recovery responses in the event of AACS anomalies.
- Command Loss - switches to redundant command reception hardware unit in an effort to reestablish command reception capability in the event of a command not being received within the specified time interval (currently set at 42 days).
- Radio Frequency Power Loss - monitors S and X band exciter and transmitter hardware, and switches to redundant units if failure is detected.
- CCS Error - responds to critical anomalous CCS hardware and software conditions. The response typically stops any ongoing sequence activities, places the CCS in a known quiescent state and waits for ground action.
- Power Recovery - responds to CCS tolerance detector trip or S/C undervoltage power utilization condition by eliminating power load in a predetermined manner.

Table 5 - Fault Protection Algorithms

Power Reduction Plan

Electrical power for the Voyager S/C is provided by RTGs. Due to the radioactive decay of the plutonium fuel source, the electrical power provided by the RTGs is continually declining, with the current rate of decay being approximately 5.2 watts per year. In order to maintain an adequate power margin, it is necessary to periodically reduce power usage, by turning off power loads. Table 6 summarizes the key mission changes resulting from the power reduction plan for **the** two S/C. This plan preserves the operation of the FPW instruments (MAG, PLS, LECP, CRS, PWS, PRA) until approximately 2015 at which time they will be turned off, one at a time, as necessary. The order of turn off shall be dependent upon the instrument status at that time.

	Voyager 1	Voyager 2
• Terminate UV data acquisition and scan platform operations	2000	1998
• Terminate gyro operations (MAGROL & ASCAL calibrations)	2007	2004
• Start turning off FPW instruments	2015	2016

Table 6 - Key Power Management Driven Mission Changes

Voyager Project Home Page

For more information and current status of the Voyager Project, the World Wide Web address of the Voyager Project Home Page is http://vraptor.jpl.nasa.gov/voyager/voyager.html

Recommendations For Consideration By Future Missions

1. Design the S/C data system to meet existing ground system interfaces, and avoid requiring unusual data formats, data modes, derived parameters, etc.

ii. Build ample margins into the S/C subsystems (telecommunications, electrical power, compute] memory, propellant, etc.) that will eliminate subsystem margin management and reduce required subsystem analysis

iii. Design the data return plan to minimize utilization of DSN resources. This implies on-board data storage capable of storing days worth of data before requiring playback. Avoid real time data return missions.

iv. Incorporate on-board subsystem trend analysis/alarm monitoring capability that only requires downlinking the trend analysis and alarm monitoring parameters for normal operations.

v. If possible, utilize shared mission operations with another project. This is feasible if: the sharing projects do not have missions that conflict with one another in terms of peak activity periods; a unique MOS is not required and; greatly different operating skills arc not required to operate each mission

vi. Minimize real time mission control support by implementing automated monitoring capabilities, i. c., a VA MPIRE-like alarm monitoring and notification tool.

vii. Foster a concurrent MOS-S/C engineering process. Utilize a simulation capability to develop and demonstrate ground system/spacecraft interfaces and compatibility as the S/C evolves. These same ground nodes will later serve to support delivery of science data, support inputs to the uplink process, and support S/C subsystems analysts in the event of a S/C anomaly.

Acknowledgments

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